Pion Production in Neutrino-Nucleon Reactions

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Abstract. We construct a model for the weak pion production off the nucleon, which in addition to the weak excitation of the $\Delta(1232)$ resonance and its subsequent decay into $N\pi$, it includes also some background terms required by chiral symmetry. We re-fit the $C_5^A(q^2)$ form factor to the flux averaged $\nu_\mu p \to \mu^- p \pi^+$ ANL q^2-differential cross section data, finding a substantially smaller contribution of the Δ pole mechanism than traditionally assumed in the literature. We also show that the interference between the Delta pole and the background terms produces parity-violating contributions to the pion angular differential cross section.

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INTRODUCTION

The pion production processes from nucleons and nuclei at intermediate energies are important tools to study the hadronic structure and play an important role in the analysis of the present neutrino oscillation experiments, where they constitute a major source of uncertainty in the identification of electron and muon events. Therefore, it is important to understand nuclear medium effects in the production of leptons and pions induced by the atmospheric as well as accelerator neutrinos used in these oscillation experiments. To this end, the starting point should be a correct understanding of the reaction mechanisms in the free space. In this talk, we focus on the weak pion production off the nucleon driven both by Charged and Neutral Currents (CC and NC) at intermediate energies. The model presented here will allow us to extend the results of Refs. [1] for CC and Ref. [2] for NC driven neutrino-nucleus reactions in the quasielastic region, to higher excitation energies above the pion production threshold up to the $\Delta(1232)$ peak.

There have been several studies of the weak pion production off the nucleon at intermediate energies [3]–[7]. Most of them describe the pion production process at intermediate energies by means of the weak excitation of the $\Delta(1232)$ resonance and its subsequent decay into $N\pi$, and do not incorporate any background terms. In this talk, we also consider some background terms, required by chiral symmetry. Their contribution[1] is sizeable even at the $\Delta(1232)-$resonance peak and it turns out to be

[1] Some background terms were also considered in Refs. [4] and [6]. In the latter reference, the chiral counting was broken to account explicitly for ρ and ω exchanges in the $t-$channel, while the first work is not consistent with the chiral counting either and it uses a rather small axial mass (≈ 0.65 GeV), as well.

dominant near pion threshold. We re-adjust the $C_5^A(q^2)$ form–factor that controls the largest term of the $\Delta-$axial contribution, and find corrections of the order of 30% to the off diagonal Goldberger-Treiman relation (GTR) when the ANL bubble chamber cross section data [8] are fitted. Such corrections would be smaller if the BNL data [9] were considered. Additional results and all sort of details can be found in Ref. [10].

THEORETICAL FRAMEWORK

We will focus on the neutrino–pion production reaction off the nucleon driven by charged currents, $\nu_l(k)+N(p)\to l^-(k')+N(p')+\pi(k_\pi)$, though the generalization of the obtained expressions to antineutrino induced reactions and/or NC driven processes is straightforward (see Ref. [10]). The unpolarized differential cross section, with respect to the outgoing lepton and pion kinematical variables is given in the Laboratory (LAB) frame (kinematics is sketched in Fig 1) by

$$\frac{d^5\sigma_{\nu_l l}}{d\Omega(\hat{k}')dE'd\Omega(\hat{k}_\pi)}=\frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2}\int_0^{+\infty}\frac{d|\vec{k}_\pi||\vec{k}_\pi|^2}{E_\pi}L_{\mu\sigma}^{(\nu)}\left(W^{\mu\sigma}_{\mathrm{CC}\pi}\right)^{(\nu)} \tag{1}$$

with G the Fermi constant and L and W the leptonic and hadronic tensors, respectively. The leptonic tensor is given by $[\varepsilon_{0123}=+1,\ g^{\mu\nu}=(+,-,-,-)]$: $L^{(\nu)}_{\mu\sigma}=k'_\mu k_\sigma+k'_\sigma k_\mu-g_{\mu\sigma}k\cdot k'+\mathrm{i}\varepsilon_{\mu\sigma\alpha\beta}k'^\alpha k^\beta$. The hadronic tensor includes all sort of non-leptonic vertices,

$$(W^{\mu\sigma}_{\mathrm{CC}\pi})^{(\nu)}=\overline{\sum_{\mathrm{spins}}}\int\frac{d^3p'}{(2\pi)^3}\frac{\delta^4(p'+k_\pi-q-p)}{8ME'_N}\langle N'\pi|j^\mu_{\mathrm{cc}+}(0)|N\rangle\langle N'\pi|j^\sigma_{\mathrm{cc}+}(0)|N\rangle^* \tag{2}$$

with $q_\mu=k_\mu-k'_\mu$, M the nucleon mass and $j^\mu_{\mathrm{cc}+}$ the quark CC. Lorentz invariance restricts the dependence of the cross section on ϕ_π (pion azimuthal angle),

$$\frac{d^5\sigma_{\nu_l l}}{d\Omega(\hat{k}')dE'd\Omega(\hat{k}_\pi)}=\frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2}\left\{A+B\cos\phi_\pi+C\cos2\phi_\pi+D\sin\phi_\pi+E\sin2\phi_\pi\right\} \tag{3}$$

with A,B,C,D and E real, structure functions, which depend on q^2, $p\cdot q$, $k_\pi\cdot q$ and $k_\pi\cdot p$. To compute the background contributions to the $\langle N'\pi|j^\mu_{\mathrm{cc}\pm}(0)|N\rangle$ matrix elements, we start from a SU(2) non-linear σ model involving pions and nucleons, which implements the pattern of spontaneous chiral symmetry breaking of QCD. We derive the corresponding Noether's vector and axial currents and those determine, up to some form-factors[2], the contribution of the chiral non-resonant terms. To include the Δ resonance, we parametrize the $W^+N\to\Delta$ hadron matrix element as in [3] with the set of form-factors used in [7]. In particular, for the $C_5^A(q^2)$ form–factor that controls the largest

[2] The form factor structure is greatly constrained by CVC and PCAC and the experimental data on the q^2 dependence of the WNN vertex.

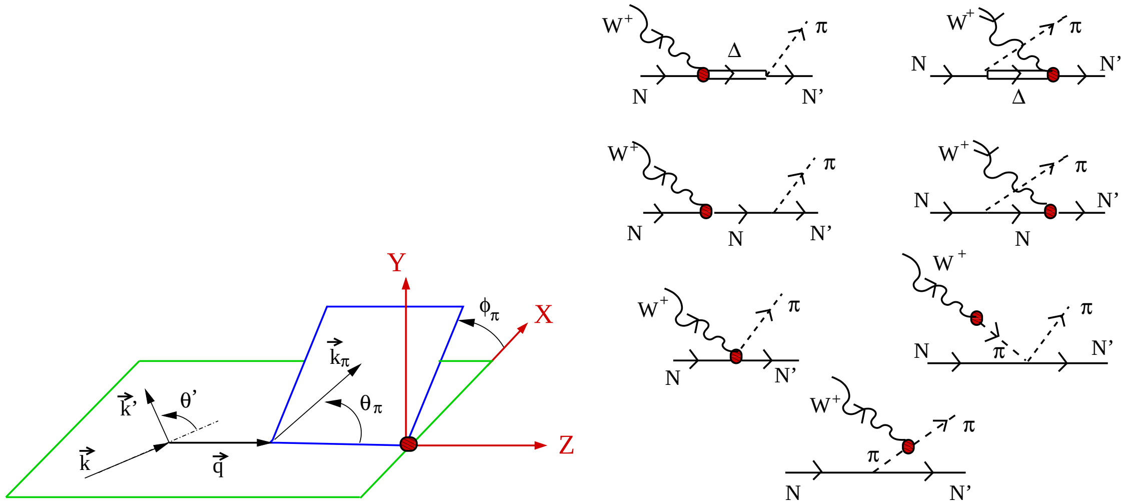

FIGURE 1. Left: Definition of the different kinematical variables used through this work. Right:Model for the $W^+N \to N'\pi$ reaction. It consists of seven diagrams: Direct and crossed $\Delta(1232)-$ (first row) and nucleon (second row) pole terms, contact and pion pole contribution (third row) and finally the pion-in-flight term. The circle in the diagrams stands for the weak transition vertex.

term of the $\Delta-$axial contribution, we use

$$C_5^A(q^2) = \frac{1.2}{(1-q^2/M_{A\Delta}^2)^2} \times \frac{1}{1-\frac{q^2}{3M_{A\Delta}^2}}, \quad \text{with} \;\; M_{A\Delta} = 1.05\,\text{GeV}. \tag{4}$$

which leads to a reasonable description [7] of the ANL data. C_5^A at $q^2 = 0$ is set to the prediction of the off-diagonal GTR. The model consists of 7 Feynman diagrams (right panel of Fig. 1) constructed out of the $WN \to N$, $WN \to \Delta$, $WN \to N\pi$, $W\pi \to \pi$ and the $W \to \pi$ weak transition vertices and the πNN, $\pi\pi NN$ and $\pi N\Delta$ strong couplings. This model is an extension of that developed in Ref. [11] for the $eN \to e'N\pi$ reaction.

RESULTS AND CONCLUSIONS

In Fig. 2 we present the flux averaged q^2 differential cross sections for the reaction $\nu_\mu p \to \mu^- p\pi^+$ measured by the ANL and BNL experiments, with the πN invariant mass cut $W \leq 1.4$ GeV. The agreement with the ANL data is certainly worsened when the background terms, required by chiral symmetry, are considered (dashed-dotted line). This strongly suggests the re-adjustment of this form–factor. A χ^2-fit provides

$$C_5^A(0) = 0.867 \pm 0.075,\; M_{A\Delta} = 0.985 \pm 0.082\,\text{GeV},\;\; \chi^2/dof = 0.4 \text{ and } r = -0.85 \tag{5}$$

We observe a correction of the order of 30% to the off diagonal GTR. Results for total and differential neutrino cross sections, antineutrino and NC cross sections for different isospin channels can be found in Ref. [10]. In general, the inclusion of the chiral symmetry background terms brings in an overall improved description of data as compared to the case where only the ΔP mechanism is considered.

The NC cross section dependence on ϕ_π constitutes a potential tool to distinguish $\nu_\tau-$ from $\bar{\nu}_\tau$, below the $\tau-$production threshold, but above the pion production one [12]. The interference between the ΔP and the background terms produces parity-violating contributions [10] (structure functions D and E in Eq. (3)) to $d^5\sigma_{\nu_l l}/d\Omega(\hat{k}')dE'd\Omega(\hat{k}_\pi)$, which might be used to constrain the axial form factor C_5^A.

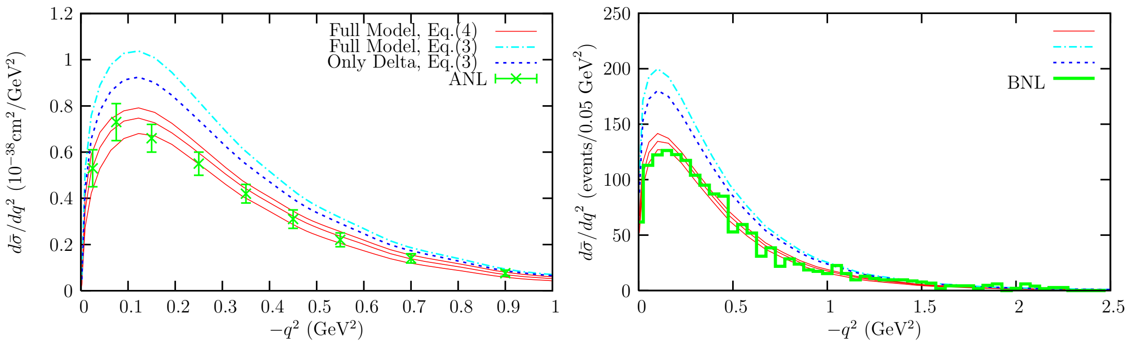

FIGURE 2. Flux averaged q^2-differential $\nu_\mu p \to \mu^- p\pi^+$ cross section $\int_{M+m_\pi}^{1.4\,\mathrm{GeV}} dW \frac{d\bar{\sigma}_{\nu_\mu\mu^-}}{dq^2dW}$ compared with the ANL [8] (left) and BNL [9] (right) experiments. Dashed lines stand for the contribution of the excitation of the Δ^{++} resonance and its subsequent decay (ΔP mechanism) with $C_5^A(0) = 1.2$ and $M_{A\Delta} = 1.05$ GeV. Dashed–dotted and central solid lines are obtained when the full model of Fig. 1 is considered with $C_5^A(0) = 1.2, M_{A\Delta} = 1.05$ GeV (dashed-dotted) and with our best fit parameters $C_5^A(0) = 0.867, M_{A\Delta} = 0.985$ GeV (solid). In addition, we also show the 68% CL bands from Eq. (5).

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